Experimental assessment of strain gradient plasticity theories

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INTRODUCTION

Classical plasticity theories generally assume that the stress at a point is a function of strain at that point only. However, when gradients in strain become significant, this localization assumption is no longer valid. These conventional models fail to display a 'size effect'. This effect is seen experimentally when the dimension characteristic of the physical phenomenon involved is on the order of the microstructural scale of interest. Under these conditions, strain gradients are of a significant magnitude as compared to the overall strain and must be considered for models to accurately capture observed behavior.

The mechanics community has been actively involved in the development of strain gradient theories for many years. Recently, interest in this area has been rekindled and several new approaches have appeared in the literature. Two different approaches are currently being evaluated. One approach considers strain gradients as internal variables that do not introduce work conjugate higher order stresses. Another approach considers the strain gradients as internal degrees of freedom that requires work conjugate higher order stresses. Experiments are being performed to determine which approach models material behavior accurately with the least amount of complexity. A key difference between the two models considered here is the nature of the assumed boundary conditions at material interfaces. Therefore, we are investigating the deformation behavior of metal/sapphire interfaces loaded under simple shear. To determine the lattice rotations near the boundary, we are examining the samples with submicron X-ray methods and with diffraction techniques in the transmission electron microscope. The experimentally found boundary conditions shall be subsequently used to determine whether the simpler internal variable model is adequately descriptive. This information will also be included in the mesoscale simulations to be carried out as part of the LLNL Multiscale Materials Modeling Project.

BACKGROUND

Although not predicted by classical models, an increase in flow stress is seen during deformation when the observed phenomena is on the order of a micron and inhomogeneties are present. For example, Fleck et.al. [1] showed that when loaded in torsion, a wire displays greater strength for smaller radii. Others authors have observed this type of effect in other systems, including bending [2], indentation hardness [3], and particle hardened alloys [4]. The increase in hardness under these conditions is attributed to the additional dislocations needed for compatibility. These dislocations are commonly referred to as geometrically necessary dislocations [5]. The presence of these dislocations can be ignored and continuum theories applied at large size scales since gradients in strain are small. However, at smaller size scales, more dislocations are formed in a smaller area, resulting in large strain gradients and higher flow stresses. When strain gradients become significant, this localization assumption in continuum theories is no longer valid [6]. This must be accounted for in a non-local theory to accurately reflect material response. Two distinct classes of models that extend classical theories to include strain gradient effects are currently being evaluated. Fleck and Hutchinson [7] have developed one approach (referred to as the FHS model [8]) that considers strain gradients as internal degrees of freedom and requires thermodynamic work conjugate higher order stresses, which need additional boundary conditions. Acharya and Bassani [9] have developed an alternative approach in which a strain gradient term is included in the hardening function. In this method, the strain gradients are considered to be internal variables, which do not introduce higher order stresses or additional boundary conditions. This approach has the advantages that it is simpler overall, preserves the structure of the classical boundary value problem, and can easily be implemented into existing finite element codes. However, the higher order theory may be more predictive because it allows for constraints on strain to be enforced at interfaces. The additional boundary conditions in the higher order theory allow for the presence of a boundary layer. Specifically, Fleck and Hutchinson [7] determined theoretically that a boundary layer of lattice rotation should be present at an interface between dissimilar materials loaded under remote simple shear. Since boundary layers are not predicted in Acharya and Bassani's approach, detecting the presence of these layers at interfaces will supply critical information in the continued development of strain gradient plasticity theories. Boundary layers seem likely in real materials, since stress fields that are strongly affected by boundaries [10] govern dislocation motion. The presence of a boundary layer, however, has not yet been definitively determined. Although previous experimental work on bicrystals by Sun et.al [11] suggests the presence of a boundary layer, the data are difficult to interpret due to the movement of the grain boundary. Therefore, experiments performed at a metal-ceramic interface are proposed to determine deformation behavior without the complication of grain boundary movement.

EXPERIMENTAL PROCEEDURE

The deformation behavior near an interface is investigated using samples composed of 25μm thick aluminum foils sandwiched between sapphire rods (see [12] for more details). An ultra-high vacuum diffusion-bonding machine [13] is used to bond the two materials. The metal layer is sheared using asymmetric four point bending. This test is used to achieve a uniform simple shear stress state. This stress state is needed to shed light on existing strain gradient models, because each model considered predicts different behavior under this condition. Finite element modeling is used to simulate this experiment in order to confirm the homogeneity of the deformation. The sapphire is modeled as an isotropic elastic material and the metal is modeled as a J_2 linear hardening material. The modeling confirms that the metal layer is under a homogeneous stress state, but does exhibit some edge effects in the strain profiles. This will not affect the experimental results, because observations are only made in the center of the sample.

In order to detect the presence of a boundary layer in the aluminum near the sapphire, the lattice rotations need to be measured from the center of the aluminum layer to an interface in one micron steps. To measure the rotation, the mechanically tested samples were cut into slices for observation of diffraction patterns in a transmission electron microscope (TEM). Unfortunately, standard TEM sample preparation methods cause the aluminum to recrystallize, so a non-destructive method is desired. Unlike most X-ray techniques, the submicron X-ray technique developed at the Advanced Light Source (ALS) [14] uses a small enough spot size to properly investigate the lattice rotation changes in these samples. Unfortunately, the noise from the surface damage layer formed during the polishing of the aluminum is obscuring the signal from the Laue patterns in the bulk region. It has not been possible to fully analyze this data. From some initial analysis, there does appear to be a measurable change in lattice rotation as the interface is approach. However, improved sample preparation techniques to produce a stronger signal need to be employed to confirm this initial indication. Confirming or refuting the presence of this boundary layer is the primary result of the experimental program. If the boundary layer is present, its characterization will be critical in providing parameters for the FHS model. Continued improvement of the model will be facilitated by further experimental results generated by continued investigations. The cyclic feedback of information between experiments and modeling has proven to be successful in other parts of the Multiscale Materials Modeling Project at Lawrence Livermore National Laboratory.

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